Cold Atom Space Clock with Counter-Propagating Atoms

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We discuss the feasibility to realize a space cold atom clock with counter-propagating cold atoms in microgravity. The design of the space clock is based on atomic beam clock with a Ramsey cavity, except a magneto-optical trap (MOT) is placed at each side. Cold atoms are launched from MOTs at both side of the clock simultaneously and move at counter-direction towards each other. The velocity of launched atoms is precisely controlled to the Ramsauer-Townsend resonance so that no additional collision frequency shift is taken place. Such a configuration can efficiently cancel the frequency shift led from cavity phase shift and increase the signal to noise.

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In 1955, the first atomic frequency standard, using a Cs beam excited by means of the separated oscillatory field, was completed by Essen and Parry [1]. The approach was proposed by Ramsey in 1950 [2]. In the Ramsey atomic clock, an atomic beam is formed in an oven and are allowed to drift freely in high vacuum into an interaction region formed by a microwave structure called the Ramsey cavity. The structure is generally with a U-typed waveguide. This arrangement creates two short microwave interaction regions of length ℓ, separated by a relatively large distance L. After traversing the first interaction region, atoms are exposed to the microwave field for a short time, which depends on the distance L, and then enter the second interaction region. Similar to the technique of magnetic resonance, transitions of atoms are excited between the two special levels. The advantage of the Ramsey type atomic clock is that interferences take place between the excitation in the two interaction regions, leading to a series of fringes which is called "Ramsey fringes". A narrow resonance can be obtained by a factor of the order of L/ℓ.

In experiment, it is very hard to keep the phases of microwave between two interaction regions in an accurate consistent. A small unwanted phase shift may be caused by an asymmetry in the Ramsey cavity construction, and then the central fringe will be distorted. The shift is so-called "cavity phase shift". It is necessary to cancel the cavity phase shift in theory or minimize it for improving the accuracy of Ramsey type atomic clock.

In a classical thermal cesium clock, a beam of atoms effuses from an oven and passes through a state-selecting magnet, and subsequently passes through a Ramsey microwave cavity, and then detected [3]. The velocity of thermal atoms can be as slow as 95 m/s and line width of the clock transition is typically around 60 Hz, as PTB Cs frequency standards apply [3]. In order to test the cavity phase frequency shift, in PTB's primary clock CS2, an oven and detector is placed at each end so that alternate operation of atomic beam in opposite directions can be performed [4].

In 1954 Zacharias attempted to obtain an even narrower separated oscillatory field resonance in a "fountain" experiment [5, 6]. The most important improvement in the fountain clock is using one interaction field instead of two regions. Atoms interact with the one interaction region two times in the track of up and down, and interferences taking place between twice interactions. Thus the cavity phase shift can be cancelled in theory. Unfortunately the experiment failed due to the very slow atoms being scattered away as they emerged from the thermal source.

The advent of laser cooling techniques open the door to a new approach for the fountain clock [6]. Atoms are first captured and cooled in a MOT, and then launched upwards by a technique called moving molasses. The width of Ramsey fringe for a fountain is determined by $\Delta\nu = 0.25\sqrt{g/2H}$, where g is the gravitational acceleration, and H is the maximum height of launched atoms. Typically, for a cold atom fountain clock, the width of the central Ramsey fringe is 1 Hz, which corresponds to $H = 0.3$ m. Narrower width is possible but technically difficult. For example, 0.1 Hz width requires $H = 30$ m, which is impractical.

Soon after the success of the fountain clock, people noticed that even narrower width can be realized in microgravity environment [7]. In microgravity, the atoms move at constant velocity after they are launched from a MOT, that means the slower velocity of launched atoms leads to the longer interrogation time, or the narrower width of central Ramsey fringe. In micro-gravity environment, however, the design of the fountain clock can not be adopted in the cold atom space clock, and Ramsey cavity structure is recalled again, and thus cavity

phase shift should be focused again especially for a cold atom space clock with high accuracy and stability.

In cold atom space clock, the PHARAO [7] for example, cold atoms are launched from a MOT at velocity as low as 5 cm/s, and 0.1 Hz width of central Ramsey fringes is predicted. The expected stability is $10^{-13}/\sqrt{\tau}$, where τ is the integration time, and the accuracy is up to 10^{-16}. For such a high stability and accuracy, the phase shift of the space clock's Ramsey cavity becomes more important. Certainly, it is possible to apply PTB's CS2 clock design in the space clock, and alternate operation of cold atoms in opposite direction gives the information of the cavity phase shift, but such a design wastes precious space resources.

In this paper, we propose a new type of space clock, whose design is similar to the PTB's CS2 [4], but with completely new operation mode. The new type of space clock aims at cancelling the frequency shift due to the phase difference of the Ramsey cavity and increasing the signal to noise ratio, and thus reducing the technical difficulties of the design and improving the performance of the space clock. As shown in Fig. 1, a MOT and a detection region is placed at each end. Cold atoms are launched from both MOTs simultaneously in opposite direction towards each other. Assuming Cloud A denotes the cold atoms launched from the left MOT, and Cloud B from the right MOT, Cloud A collides with Cloud B at the center of the Ramsey cavity after they pass through the first interaction region of the cavity.

In atom-atom collisions, if the atoms are treated classically as hard balls, the calculated cross section is independent of the atomic energy. In quantum mechanics, however, the atoms are considered to present a dipole-dipole interaction of typical atomic dimensions for the scattering between atoms. The solution of Schrödinger Equation for two dipole-dipole potentials shows that the cross-section in atom-atom collisions will have a minimum at some specific energies. This is a simple illustration of the Ramsauer-Townsend resonance [8]. At the Ramsauer-Townsend resonance, the atoms are transparent with each other when they collide, and frequency shift lead from collisions becomes null. Gibble *et.al.* measured the s-wave frequency shift with juggling ^{133}Cs and ^{87}Rb fountain clock [9, 10, 11]. The first Ramsauer-Townsend shift null for ^{87}Rb happens at alternate launch time delays of $\Delta t = 22$ ms between two cold atom balls, corresponding to the velocity $v_{RT} = g\Delta t/2 = 10.78$ cm/s of each ball propagating at opposite direction. At such a velocity, the collision between the Cloud A and B does not contribute additional frequency shift. For the scattering of identical

particles, the p-wave scattering does not contribute additional frequency shift.

We assume that the interrogation length of the Ramsey cavity is $L = 52.5$ cm, which gives the interrogation time $T_{RT} = L/v_{RT} = 4.9$ s when Cloud A or Cloud B moves at the Ramsauer-Townsend velocity v_{RT}. Such an interrogation time corresponds to the linewidth of central Ramsey fringe at $\Delta\nu = 0.1$ Hz. If the number of detected atoms is $N = 10^6$, we have the Allan variance

$$\sigma_y(\tau) = \frac{\Delta\nu}{\pi\nu_0\sqrt{N}}\sqrt{\frac{T}{\tau}} = 1.5 \times 10^{-14}/\sqrt{\tau} \tag{1}$$

where, $T = 10$ s which includes time for the preparation of cold atoms, state selection, interrogation time and detection, and $\nu_0 = 6.835$ GHz is the frequency of clock transition of ^{87}Rb, and τ is the integration time. If we do not consider the phase shift of the Ramsey cavity, we can average the detected atoms from both Cloud A and B such that $N = 2 \times 10^6$, which leads to the Allan variance to be reduced by a factor of $\sqrt{2}$ from Eq. (1), that is $\sigma_y(\tau) = 1.1 \times 10^{-14}/\sqrt{\tau}$.

On the other hand, with atoms' counter-propagating through a Ramsey cavity, the cavity phase shift can be accurately measured, and thus the frequency shift can be adjusted away from the error budgets of the clock. Or the frequency shift due to phase differences of the cavity can be cancelled if we average the signals from both Cloud A and Cloud B. Assuming a phase difference $\Delta\varphi$ between two zones of the Ramsey cavity, we can easily have the probability to find the two-level system in the excited state as [12]

$$p_A = \frac{1}{2}\sin^2\Omega t\{1 + \cos[2\pi(\nu - \nu_0)T_{RT} + \Delta\varphi]\} \tag{2}$$

$$p_B = \frac{1}{2}\sin^2\Omega t\{1 + \cos[2\pi(\nu - \nu_0)T_{RT} - \Delta\varphi]\} \tag{3}$$

Here, p_A and p_B are the probability for Cloud A and Cloud B, respectively. Ω is the Rabi frequency, t is the interaction time between atoms and microwave. Generally, the phase difference $\Delta\varphi$ shifts the center of Ramsey fringe by

$$\frac{\Delta\nu_\varphi}{\nu_0} = -\frac{\Delta\varphi}{2\pi\nu_0 T_{RT}} \tag{4}$$

in p_A and $-\Delta\nu_\varphi/\nu_0$ in p_B. Typically, the phase difference of a U-type Ramsey cavity can be controlled below a few hundred μrad. If we take the phase difference $\Delta\varphi = 500$ μrad for example, we have $\Delta\nu_\varphi/\nu_0 = 2.3 \times 10^{-15}$. Thus in order to get accuracy of a few 10^{-16}, the frequency shift due to the phase difference of the cavity must be carefully considered.

If we take an average over the probability of Cloud A and Cloud B, we have

$$\begin{aligned} p &= \frac{p_A + p_B}{2} \\ &= \frac{1}{2}\sin^2 \Omega t[1 + \cos 2\pi(\nu - \nu_0)T_{RT} \cdot \cos \Delta\varphi] \end{aligned} \quad (5)$$

Obviously, in p, the phase difference of the cavity does not contribute any frequency shift, but the width of the central Ramsey fringe has been broadened to

$$\Delta\nu_p = \Delta\nu + 2\Delta\nu_\varphi \quad (6)$$

Typically phase difference of the Ramsey cavity is around a few hundred μrad [3]. From Eq. (4), we have $\Delta\nu_\varphi \approx 1.6 \times 10^{-5}$ Hz when $\Delta\varphi = 500$ μrad for example, which can be neglected in Eq. (6), and thus the width broadening due to the average of the signal from both counter-propagating atoms can be neglected in the Allan variance given in Eq. (1). Since the collision between Cloud A and Cloud B, each moves at the Ramsauer-Townsend velocity, does not contribute additional frequency shift, the frequency shift due to the cavity phase difference in our system can be cancelled without additional cost.

In addition, our design has a very important function for reducing the noise of the interrogation time due to the vibrations on the space craft and variations of residual microgravity in the atoms' propagating direction. This feature was first realized by Fertig *et al.* in the design of a microgravity atomic clock with the double Ramsey cavity [13]. Fertig's design has two Ramsey cavities located at both sides of a MOT, and cold atoms are launched alternatively to each Ramsey cavity. Since the alternatively launching of cold atoms in the opposite direction does not happen at the same time, the cold atoms do not sense the same vibration and residual microgravity. In our design, however, the counter-propagating atoms through same cavity at the same time, the detected signals of Cloud A and Cloud B behave oppositely and simultaneously and thus the effect of vibrations and variations of the microgravity can be removed by the averaged signal p.

Our design has some unique features especially suitable for some experiments. For example, if the velocity of launched atoms varies, the cross-section of atom-atom scattering can be measured by our space clock even more precisely than by the juggling fountain clock. Such a measurement can give detailed data for atom-atom scattering and test the fundamental principle of quantum mechanics.

In conclusions, we have proposed a new type of cold atom space clock with counter-propagating atoms. The cold atoms move at Ramsauer-Townsend velocity so that the collision between counter-propagating atoms becomes null. We pointed out that such a null collision cross section can cancel the frequency shift lead from the phase difference of the Ramsey cavity, and also increase the signal to noise ratio. We estimated the Allan variance of such a space clock at $1.5\times10^{-14}/\sqrt{\tau}$. Besides, our design of the space clock can efficiently remove the noise due to the vibration and residual microgravity of the space craft, and thus reduce the requirement of space environment.

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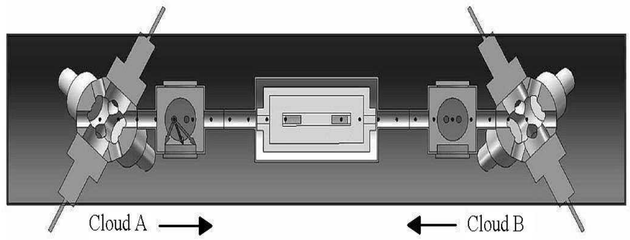

FIG. 1: Schematic diagram of cold atom space clock with counter-propagating atoms